

CONCERNING THE WHITE DWARF COOLING AGE OF M4: A REPLY TO DE MARCHI ET AL. ON “A DIFFERENT INTERPRETATION OF RECENT DEEP *HST* OBSERVATIONS”¹

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ABSTRACT

We respond to the recent paper by De Marchi et al. on the white dwarf cooling age of M4. The authors question the data analysis and interpretation that led to our conclusions in Hansen et al. in 2002. In their paper, De Marchi et al. are unable to obtain photometry as deep as ours from the same data set and therefore assert that only a lower limit to the white dwarf cooling age for this cluster of ~ 9 Gyr can be obtained. In this brief contribution we show that shortcomings in the data analysis and reduction techniques of De Marchi et al. are responsible for their inability to reach the photometry limits that our study reports. In a forthcoming paper in which the complete techniques for age determination with white dwarfs are laid out, we demonstrate that their method of fitting the luminosity function yields a spuriously low white dwarf cooling age.

Key words: globular clusters: individual (M4) — techniques: image processing — white dwarfs

1. INTRODUCTION

In early 2001, the *Hubble Space Telescope* (*HST*) obtained the deepest data set ever observed for a globular cluster, an exposure of 123 orbits centered on a field 5' from the center of the globular cluster M4. We reported an analysis of the lower main sequence of M4 (Richer et al. 2002) and a determination of the white dwarf cooling age of M4 (Hansen et al. 2002). The latter is derived from a χ^2 fit of models to the entire white dwarf luminosity function. The derived age of 12.7 ± 0.35 Gyr (1 σ statistical error only) is consistent with other age determinations for old star clusters, and with the *WMAP* concordance cosmology age (Spergel et al. 2003).

In recent contributions, De Marchi et al. (2002, 2004) performed a reanalysis of the long-exposure data from our *HST* project GO-8679 (Richer et al. 2002; Hansen et al. 2002) and were unable to reproduce results similar to ours. In particular, their photometry failed to reach as faint as ours by almost a full magnitude. This can be seen quite dramatically in Figure 1,

where we plot our color-magnitude diagram (CMD) in the white dwarf region from this data set and that of De Marchi et al. taken from their paper. Continuing, the authors claim that the only possible age constraint for M4 is that the lower limit for the white dwarf cooling age is 9 Gyr, whereas we (Hansen et al. 2002) derived a cooling age of 12.7 Gyr (updated to 12.1 Gyr in Hansen et al. 2004). The analysis of De Marchi et al. raises distressing questions about our competence both in data analysis and in interpretation. As they have already been cited by others in the literature (e.g., Möhler et al. 2004), we believe that it becomes crucial for us to respond.

The conflict raises two questions. First, why do two independent teams approaching the same data set obtain such different results? Second, what is the correct approach to fitting a measured white dwarf luminosity function? We answer the first question in this contribution and the second in detail in Hansen et al. (2004) and illustrate how the De Marchi et al. analysis fails on both counts.

2. DATA REDUCTION AND ANALYSIS

The reason De Marchi et al. are unable to reproduce the depth and quality of our CMD is purely one of data treatment. The *HST* data set under consideration, GO-8679, contains 98 F606W and 148 F814W images, each of exposure 1300 s. A first-epoch set of images taken in F555W and F814W (GO-5461) were obtained by us in 1995 (Richer et al. 1995,

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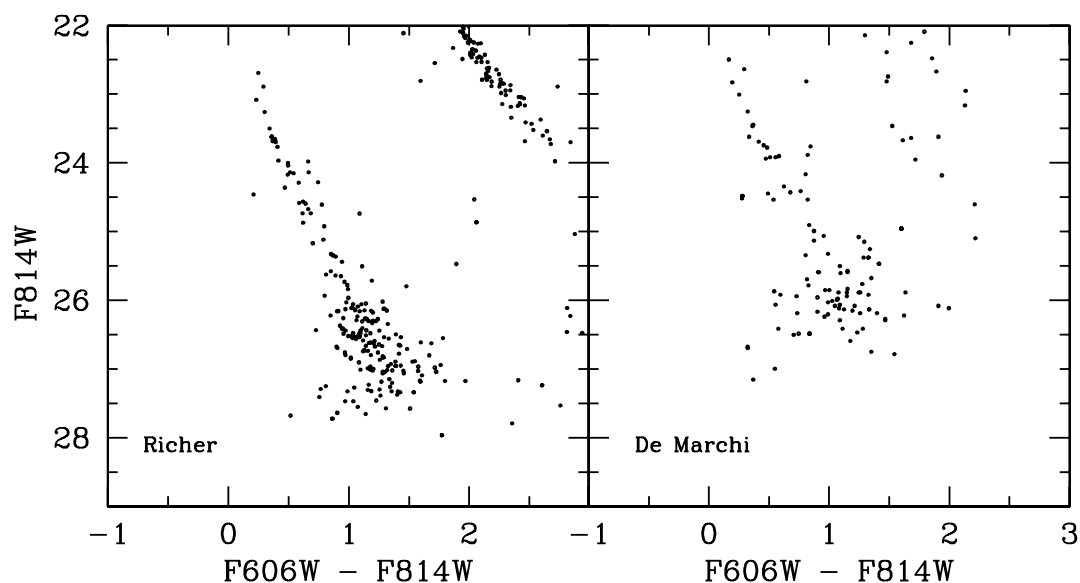


FIG. 1.—Color-magnitude diagrams in the white dwarf region from Richer et al. (2002) and Hansen et al. (2002) (*left*) compared with that of De Marchi et al. (2004, *right*), taken from their paper. In both diagrams, only stars detected in images from both epochs were included so that proper-motion selection could be made. No main-sequence stars are included in this version of the De Marchi et al. CMD. The Richer et al. CMD is fully 1 mag deeper and, significantly, exhibits much smaller scatter even at relatively bright magnitudes.

1997) and were not nearly as deep. Some care is required in getting the most out of this large and impressive data set.

In our case, after accounting for dithers, those frames corresponding to a particular epoch and filter were averaged together with pixel rejection—the n highest pixels being rejected to eliminate cosmic-ray contamination. From the *HST* WFPC2 Instrument Handbook, the mean number of pixels on a given chip affected by a cosmic-ray hit in an 1800 s exposure is about 20,000. Hence, in a stack of $N \times 1300$ s exposures we expect $0.02257N$ pixels at a given position to have suffered a hit. Taking the dispersion to be $(0.02257N)^{1/2}$ and using 5σ rejection, we find that in combining the 98 F606W images the highest 7 pixels should be rejected, while

for the 148 F814W images we should eliminate the highest 9. Our procedure thus used 93% of the available pixels in constructing the mean.

By contrast, De Marchi et al. used image association stacks produced by the pipeline software developed by the Canadian Astronomy Data Centre and the Space Telescope European Coordinating Facility (Micol & Durand 2002). This pipeline software essentially takes the median of the available pixel values and is therefore less efficient in a statistical sense than the scheme we employed, as described above. According to Zwillinger & Kokoska (2000, p. 193), the efficiency of the median ranges from 1.000 for $m = 2$, to 0.743 for $m = 3$, . . . , to 0.681 for $m = 20$ and 0.637 for $m = \infty$. Hence, De Marchi

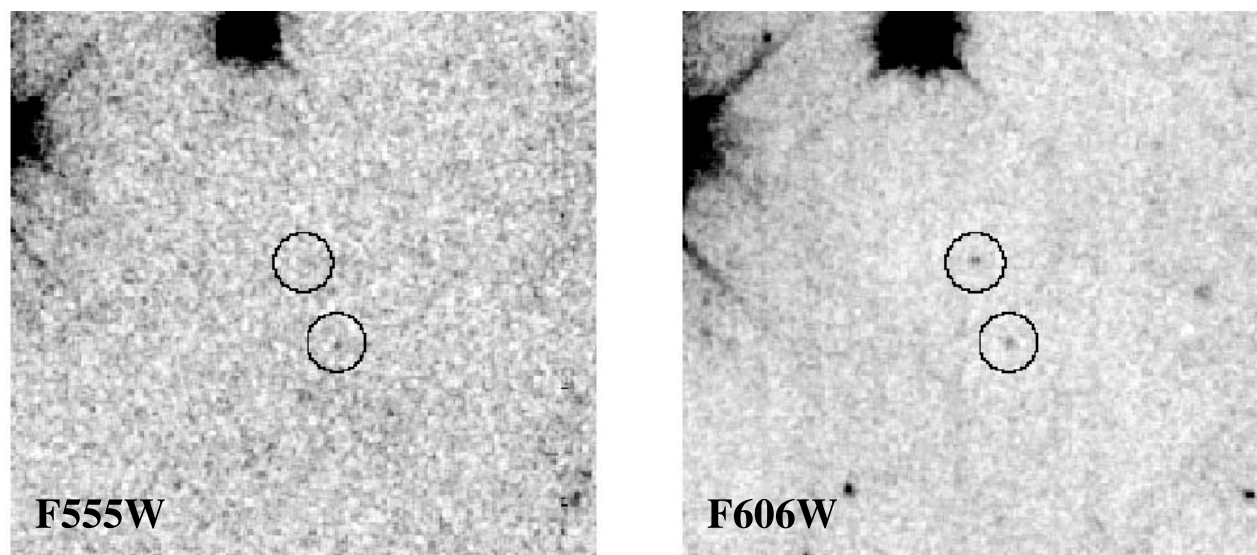


FIG. 2.—A small section of the WFPC2 WF4 chip ($17'' \times 17''$) exhibiting our stacked F606W (second epoch) and F555W (first epoch) images. The two circled objects are two of the objects discussed by De Marchi et al. (the upper is their star 2, the lower star 3), from which they claimed that objects fainter than $F814W = 27$ could not be measured on the first-epoch image. The upper object is not seen on our first epoch, as it is a galaxy whose soft image is lost in the noise. The lower of the two objects is a cluster white dwarf, easily seen in the first epoch ($S/N = 5$) with measured magnitudes of $F606W = 28.48$ and $F814W = 27.25$.

et al. effectively used less than two-thirds of the information available in the images.

We requested from the Canadian Astronomy Data Centre the image association stacks that were used by De Marchi et al. and compared them with the combined images resulting from our analysis. After allowing for the change in image scale (we expanded our images by a factor of 3 in each dimension), the main difference is that images of faint stellar objects appear perceptibly more diffuse in the pipeline-generated associations. This has the effect of making the faintest stars difficult to detect in the images De Marchi et al. used, exactly what is seen in Figure 1. We illustrate this by employing the same two stars De Marchi et al. used to claim that objects fainter than $F814W = 27.0$ could not be measured on our first-epoch frames. Recall that all we seek from the first-epoch images is a position, so that proper motions can be measured. All the photometry is carried out on the longer exposure frames. For this reason, most of our positional matching comes from the F606W-F555W pair, as the first-epoch exposures in F555W are actually quite long—31.5 ks. Figure 2 displays these two images as we produced them, with the stars discussed by De Marchi et al. circled. Clearly the lower of the two is easily visible in both frames, while the upper of the two is not seen in the shorter exposure first epoch. There is, however, a simple reason for this—it is in fact not a star at all, as our deep images clearly show it to be extended. This faint galaxy is thus lost in the noisier first-epoch image. Some specific numbers for these two objects are that each is detected at a signal-to-noise ratio (S/N) of about 8 on the long-exposure F606W image, and the upper one is not detected on the shorter F555W frame, while the lower is detected at S/N of about 5. The lower star has a proper motion completely consistent with cluster membership, and its measured magnitudes are $F606W = 28.48$ and $F814W = 27.25$. It is a cluster white dwarf, and as can be seen in Figure 1, we are able to measure stars almost 0.5 mag fainter than this one.

One crucial point is that our experiment matches long exposures in F606W (127.4 ks) and F814W (192.4 ks) with much shorter exposures in F555W (31.5 ks) and F814W (7.2 ks). The question thus arises as to how we could measure positions in the earlier epoch data for the faintest stars, where the S/N is obviously poor. For a star at $F606W = 29.0$, the expected S/N (from the WFPC2 exposure time calculator) in our deep F606W frames is 6.7, while a star at this magnitude on the shorter exposure F555W frames has $S/N = 2.5$. This is just about what we measured on our frames. The reason we can successfully measure positions of such faint objects in the first epoch is twofold.

First, we applied the finding list from the deep frames to the shallower frames. If the background noise in an image is Gaussian, then a 2.5σ positive deviation will occur in about 6 pixels out of every 1000. If, in a 750×750 image (neglecting the vignettted areas at the low- x and low- y sides of the WFPC2 CCDs) we were to mark all the 2.5σ peaks as detected astronomical objects, we would expect more than 3000 false detections. However, if we consider only the area within a 0.5 pixel radius of an object confidently detected in the long second-epoch exposure, we expect a probability $\sim \pi 0.5^2 (6/1000) \approx 0.005$ of finding a positive 2.5σ deviation that is purely the result of random noise in the first-epoch image. That is to say, we expect on the order of five false cross-identifications for every 1000 correct redetections. Even at 1.8σ , presumed reidentifications will be correct 19 times out of 20. For this reason, the knowledge that an actual astronomical object is

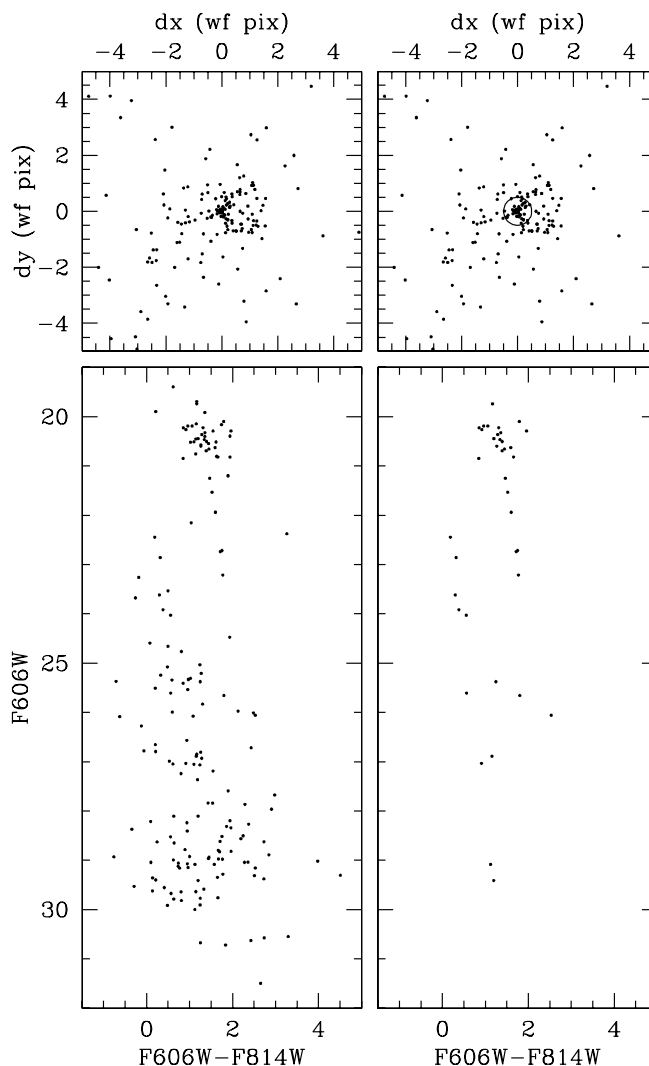


FIG. 3.—Proper-motion displacement diagram and resulting CMD from WF3 obtained when the input coordinate list for the first-epoch frames is randomly generated. The top section illustrates the proper-motion displacements in *HST* pixels over the 6 yr baseline of the data (centered on M4), while the bottom section is the CMD. The left panel contains the CMD for all the stars matched within 4 pixels in x and y , while the right one is for those stars matching within 0.5 pixels. This latter criterion is what we have used to produce the cluster CMD from which the white dwarf cooling age of M4 is derived.

present somewhere nearby based upon the long-exposure second-epoch images allows us to be confident that most of the claimed redetections on the short-exposure first-epoch images correspond to true redetections. The first-epoch astrometric positions, then, while poorer than those of the second epoch, are nevertheless good enough to distinguish stars that are moving with the cluster from stars and galaxies that are not. By contrast, De Marchi et al. made no use of this technique, and hence the shorter first-epoch frames effectively set their limiting magnitude. We checked the above by rerunning the photometry programs on the WF3 chip using a finding list with star positions generated randomly. This list contained the same number of stars as the original finding list. We then selected the objects whose photometry had converged on all frames. The resulting proper-motion displacement diagram and CMD are shown in Figure 3 and compared with the one when the true finding list is used in Figure 4. There are numerous spurious faint matches in Figure 3, but almost all disappear when the match radius of 0.5 pixels is invoked. Those objects that lie

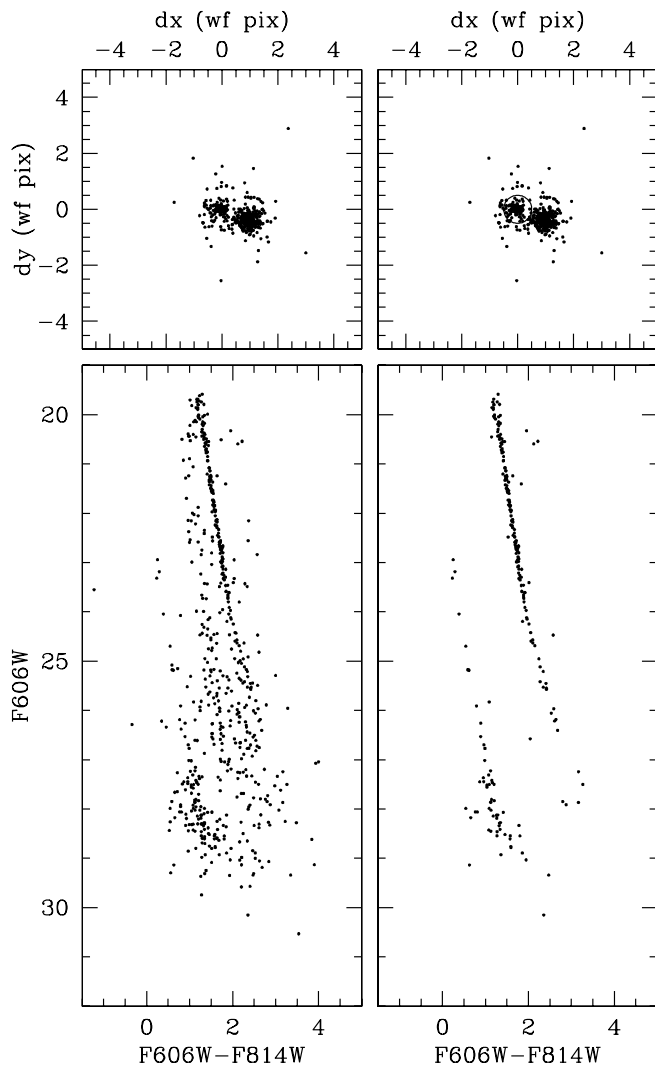


FIG. 4.—Same as Fig. 3, but with the correct coordinate system used and the matching radius set to 0.5 pixels. Figs. 3 and 4 together illustrate that spurious detections of noise spikes masquerading as faint stars are negligible in our CMDs.

outside 0.5 pixels are likely random noise spikes that have no correlated positions between frames. Figures 3 and 4 taken together show that false detections of noise spikes are not a serious source of contamination in our CMDs and that the suggestion to the contrary by De Marchi et al. is incorrect.

Secondly, the proper motions of the M4 stars are actually quite large (about 1 *HST* pixel with respect to an extragalactic background over the 6 yr time baseline; Kalirai et al. 2004). While the lower S/N image would not produce good enough photometry, the S/N is sufficient to give the centroid, which is crucial for astrometry. In Figure 5, we illustrate the quality of the proper-motion separation between cluster and field from the long and short images. Some of the brightest stars do not exhibit clean separation, because of their near saturation. However, what is clear from this diagram is that most of the field objects can be easily eliminated down to very faint magnitudes ($F606W = 29.0$) by making the generous proper-motion cut within a total value of 0.5 pixels ($\sim 8 \text{ mas yr}^{-1}$) of that of the mean cluster motion over the 6 year baseline of the observations. Nowhere do De Marchi et al. illustrate their displacement measurements.

The analysis techniques of De Marchi et al. compounded the effect of their somewhat lower quality images. Their approach uses aperture photometry to measure the stellar magnitudes. We employ point-spread function fitting, which clearly has the advantage of just using the pixels with the largest signal—thus reducing the sky contribution—a critical issue when attempting to measure faint stars. The effect of this is obvious even along the brighter portion of the white dwarf cooling sequence, where the De Marchi et al. diagram exhibits significantly larger scatter (see Fig. 1). Further, as we mentioned above, we use the positional information from the deepest frames in carrying out the photometry on the shorter exposure frames. By contrast, De Marchi et al. made no use of this information. *This has the effect of allowing the depth of the first-epoch images alone to set their limiting magnitude.*

3. OTHER ISSUES

In a forthcoming paper (Hansen et al. 2004), we consider in some detail the host of systematic effects in the white dwarf cooling age determination. In that contribution we will comment in detail on some of the points raised by De Marchi et al., such as distance modulus, reddening, and mass function. Here we have only considered reduction and analysis of the data. With regard to these data, we offer our stacked images and finding lists to anyone wanting to use them, and in Richer et al. (2004) we have presented the complete photometry lists.

On one point we agree with De Marchi et al.—the pursuit of globular cluster white dwarfs is an important and interesting scientific goal. However, it is also an extremely expensive project in terms of telescope time, and we have a responsibility to take the time to give the analysis significant thought

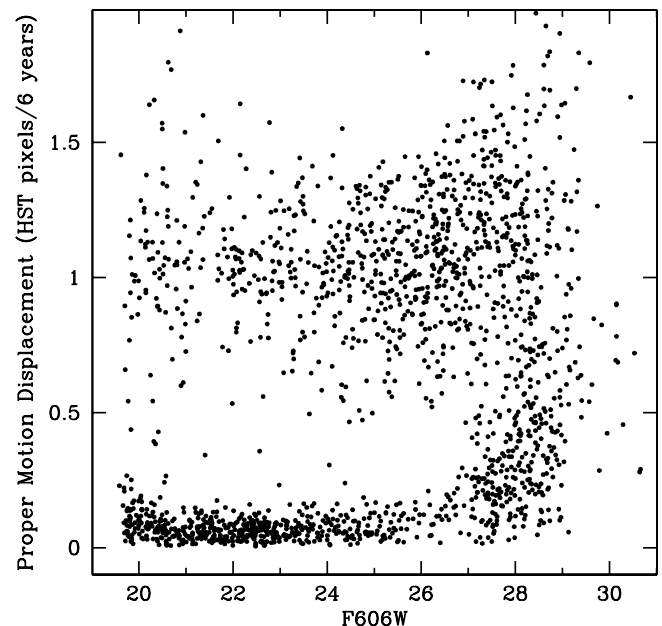


FIG. 5.—Total proper-motion difference between M4 and background/foreground objects as a function of magnitude for all the stars in the M4 images. In this diagram, the motion is zero-pointed on M4 and the displacement is given in *HST* pixels over the 6 yr baseline of the observations. The M4 stars are those along the bottom, while the field objects scatter above. The M4 internal motion is not resolved, but the dispersion in the field is. In order to separate the cluster from the field, all objects possessing motion within 0.5 pixels of that of M4 were assigned cluster membership. It is clear from this diagram that proper-motion selection can be made down to a magnitude as faint as $F606W = 29$.

and effort, to come up with the best possible analysis. We would be delighted if we could detect the truncation of the white dwarf luminosity function and hope to do so in future work. However, until such time we reiterate the point (and demonstrate its correctness in Hansen et al. 2004) that there is abundant age information in the white dwarf luminosity function and it can be modeled.

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